UNCLASSIFIED

AD NUMBER
AD519839

CLASSIFICATION CHANGES
TO: **unclassified**
FROM: **confidential**

LIMITATION CHANGES
TO: Approved for public release, distribution unlimited
FROM: Distribution authorized to U.S. Gov't. agencies only; Test and Evaluation; 15 OCT 1971. Other requests shall be referred to Office of Naval Research, Arlington, VA 22203.

AUTHORITY
ONR ltr 22 Mar 1979; ONR ltr 22 Mar 1979

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San Diego, California 92152

ADA SEPARABLE SUBMARINE STUDY (U)

Victor C. Anderson and H. P. Rumble

Sponsored by
Advanced Research Projects Agency
through
Office of Naval Research
N00014-69-A-0200-6002
NR 260-103

"TEST + EVALUATION

ARLINGTON, VA 22217

15 October 1971

SIO REFERENCE 71-26

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY *(Corporate author)*	2a. REPORT SECURITY CLASSIFICATION
University of California, San Diego, Marine Physical Laboratory of the Scripps Institution of Oceanography, San Diego, California 92152	CONFIDENTIAL
	2b. GROUP

3 REPORT TITLE

ADA SEPARABLE SUBMARINE STUDY (U)

4 DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
SUMMARY - 10/15/70 to 10/14/71

5 AUTHORS *(First name, middle initial, last name)*

Victor C. Anderson and H. P. Rumble

6 REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO OF REFS
15 October 1971	15	6

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
Advanced Research Projects Agency through Office of Naval Research	SIO Reference 71-26
b. PROJECT NO N00014-69-A-0200-6002	
c. NR 260-103	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	MPL-C-70/71

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Distribution limited to U. S. Government agencies only; 10/15/71. Other requests for the document must be referred to the Office of Naval Research (Code 466).
ARLINGTON, VA. 22217

11. Supplementary Notes	12. Sponsoring Military Activity
	Office of Naval Research

12. Abstract (UNCLASSIFIED)

This is a summary of the initial study phase for the ADA (Advanced Detection Attack) separable submarine. The contrasting functions of the two units are described and a number of alternative configurations are presented. Trade-offs between cost of structural materials and cost of buoyancy materials are shown graphically, with an indication of the least cost combination. Preliminary volume estimates are given for each of the hulls. A suggested alternative scheme involving three hulls instead of two is discussed. Selected aspects of the mating or docking operation are analyzed mathematically, and parametric curves showing the relationships among the important factors are presented. A preliminary estimate of the optimum frequency for a passive detection sonar array is calculated.

The body of this report is classified CONFIDENTIAL
because of the totality of ideas contained therein.

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SIO REFERENCE 71-26

15 Oct 1971

19 p.

*Summary rept.
15 Oct 70—14 Oct 71,*

F. N. Spiess, Director
MARINE PHYSICAL LABORATORY

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217400

MPL-C-70/71,
SIO-Ref-71-26

ii

ADA SEPARABLE SUBMARINE STUDY (U)

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ABSTRACT

This is a summary of the initial study phase for the ADA (Advanced Detection Attack) separable submarine. The contrasting functions of the two units are described and a number of alternative configurations are presented. Trade-offs between cost of structural materials and cost of buoyancy materials are shown graphically, with an indication of the least cost combination. Preliminary volume estimates are given for each of the hulls. A suggested alternative scheme involving three hulls instead of two is discussed. Selected aspects of the mating or docking operation are analyzed mathematically, and parametric curves showing the relationships among the important factors are presented. A preliminary estimate of the optimum frequency for a passive detection sonar array is calculated.

I. INTRODUCTION

The divergence of operational requirements for submarines has led to the concept of a separable submarine consisting of two parts, each part being optimized for a different purpose. The ADA (Advanced Detection Attack) submarine has one part, the "D" hull, with large dimensions and low speed designed for optimum sonar reception; the other, the "A" hull, being designed as a specialized high-speed attack platform. Combined, they comprise a third vehicle type with operating characteristics differing from those of either by itself.

This report summarizes the initial phase of the work done at the Marine Physical Laboratory. The emphasis has been on a broad overview of the project with the aim of delineating areas of experimental hardware development or technological research which could be the basis of later phases of the program.

II. CONFIGURATION STUDIES

The basic concept described in Appendix II of Ref. 1 is reproduced here as Fig. 1. With this as a starting point, a number of alternative arrangements for the "D" hull were considered. A few of the other configurations that were discarded are shown in Fig. 2. The intersecting sphere type of pressure hull was first replaced by a cylindrical type which is much easier to fabricate. With the hulls on a common horizontal axis, Fig. 2a, the access between the "A" and "D" units was not convenient.

The arrangement of Fig. 2b provided for access from the top of the "A" unit to a transverse section of the "D" hull but had the disadvantage of difficult access, from above, to the major volume of the "D" unit available for external stowage of encapsulated weapons, stores, and other items.

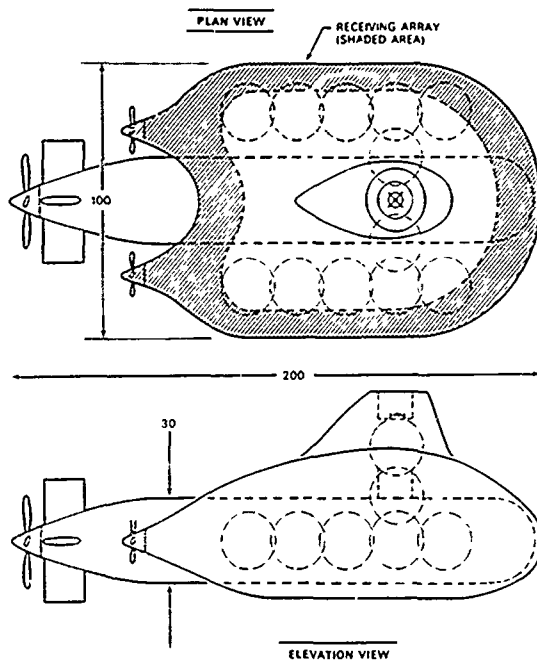In Fig. 2c the relative positions of the "A"

Fig. 1. ADA submarine concept as presented in Ref. 1.

and "D" units were reversed from those of Fig. 2b. The access to the "D" unit for external stowage is improved.

A double-decked arrangement of shorter pressure hull sections for the "D" unit is shown in Fig. 2d. This decreases the long distances between compartments at the extremities of the hull and provides, in the upper hulls, volumes that may be relatively free of traffic and thus well-suited for sonar rooms. This figure also shows the sonar array changed to an inclined plane arrangement rather than a convex curve.

Figure 3 presents the current status of the configuration study. The diameter of the transverse connecting sections is reduced to permit lowering the "A" unit to give a reduced overall height. Access to topside from the "D" unit is indicated.

An estimate of a suitable operating frequency band for the large aperture passive sonar is made in Appendix I. On the basis of this estimate, the interelement spacing would be about 1.1 ft. Figure 4 shows a typical portion of the proposed concept of the conformal sonar array that will be a major feature of the "D" hull unit. The individual transducer elements are shown mounted at the tips of pyramidal
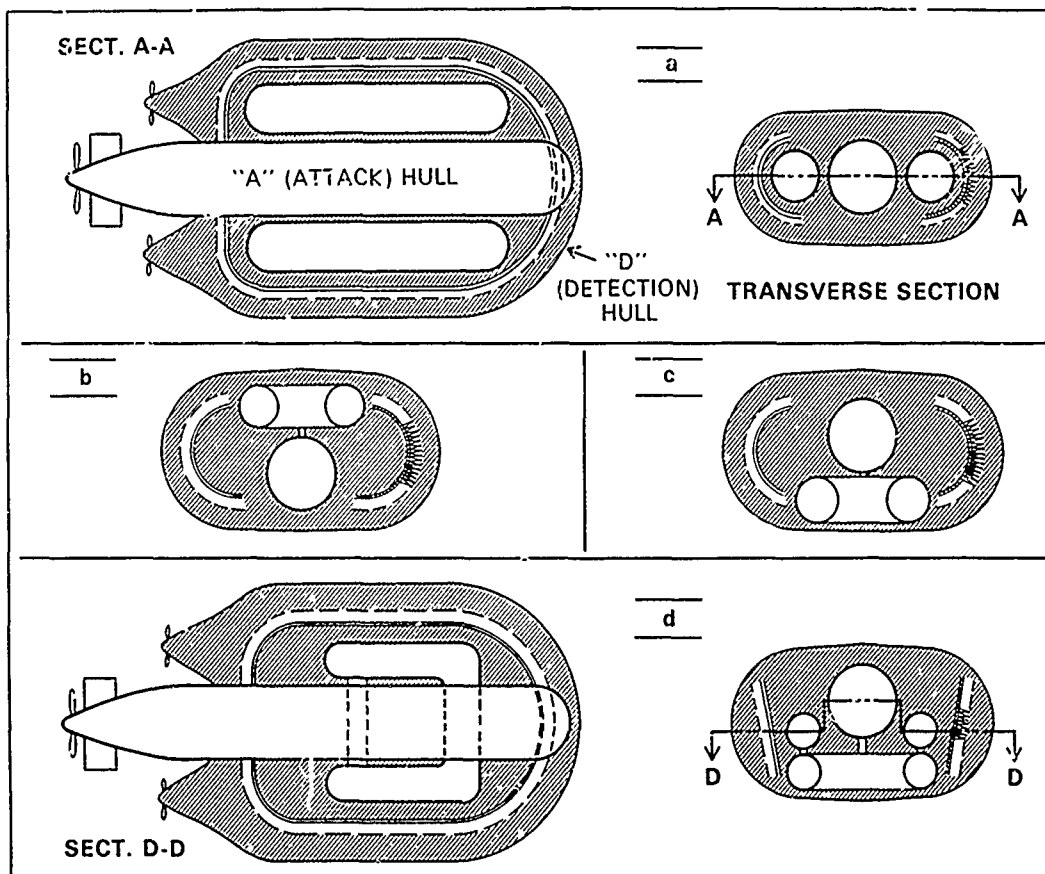

Fig. 2. Candidate ADA submarine configurations.
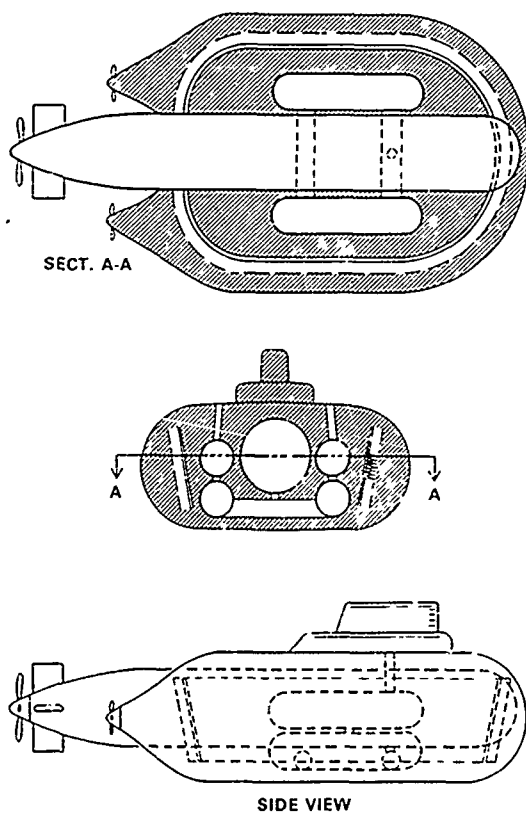
SECT. A-A

A A

SIDE VIEW

Fig. 3. Latest ADA submarine configuration.

acoustic baffles, which hopefully could be made of a neutrally buoyant material. The surface immediately inboard of the array is visualized as being treated to reduce the transmission of sound and vibration from within the hull. Layers of rubber enclosing a volume of viscoelastic fluid interspersed with steel mesh is one suggested sound-isolation treatment.

The volume between the transducer-supporting baffles, including the volume outboard of the transducers, will contain sea water for acoustic transparency, at a pressure slightly above ambient to keep the outer skin (or dome) in the desired shape. The dome itself consists of two rubber skins with the space between containing sea water at a pressure somewhat higher than the interior pressurized volume.

Also indicated on Fig. 4 is the buoyant fill material in the volume between the pressure hull and the sonar array. This is the shaded volume of the "D" unit inboard of the sonar arrays in Fig. 3, part of which would be used for wet storage of encapsulated weapons.

DOUBLE OUTER SKIN FILLED WITH
PRESSURIZED WATER (12" TOTAL THICKNESS)

VOLUME FILLED WITH
WATER & PRESSURIZED

TRANSDUCER
ELEMENTS

BAFFLES

BUOYANT FILL
MATERIAL

RUBBER LAYERS WITH STEEL MESH AND
VISCOELASTIC FLUID (3" TOTAL THICKNESS)

STEEL PRESSURE
HULL PLATING
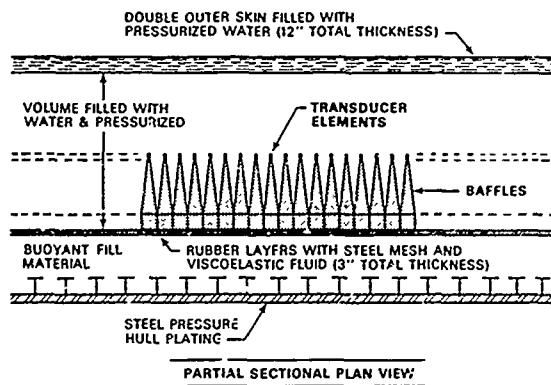
PARTIAL SECTIONAL PLAN VIEW

Fig. 4. Arrangement of receiving array, acoustic baffles and sound isolation.

To provide a basis for estimating propulsion power requirements for the "A" and "D" hulls, a velocity profile for 100 days of operation was postulated as shown in Fig. 5. This postulated velocity profile has been used by the Ordnance Research Laboratory to project fuel and oxidizer volume requirements which in turn have been used for the hull size estimates of this study.

ASSUMED VELOCITY PROFILE
FOR 100 DAYS OPERATION

	MODE OF OPERATION	SPEED, KNOTS	TIME DAYS	TIME HRS
1	MATED (EN ROUTE TO STATION)	15	15	
2	"D" UNIT SEPARATELY	3 - 5	70	
	"A" UNIT SEPARATELY	7	38	
		15	20	
		25	10	
		35		30
		45		10
3	MATED (RETURN ROUTE)	15	15	

Fig. 5. Assumed velocity profile for 100 days operation.

III. STRUCTURAL/BUOYANCY MATERIAL COST COMPARISONS

The existence of significant amounts of buoyancy outside the pressure hull of the "D" unit provides an opportunity for achieving a deep-diving pressure hull without having to resort to the more expensive, exotic hull materials. This concept has been used in several small research submersibles but has not been applied to military submarines for a variety of reasons.

To investigate in a preliminary way the cost implications of this added buoyancy concept, a set of assumptions for unit costs were made as shown in Fig. 6. These values could be debated at great length but our purpose is not one of fixing absolute cost levels, but rather it is one of comparing costs of several materials. Because of uncertainty as to the cost of titanium structures, two values were used and similarly five values of cost of buoyancy material were used in the comparison.

ASSUMED COST FACTORS

MATERIAL	COST PER LB IN DOLLARS
HY80 STEEL	2
HY130 STEEL	5
HY180 STEEL	15
TITANIUM 120	20 AND 50
BUOYANCY	1, 2, 5, 10 AND 20

Fig. 6. Assumed cost factors for pressure hull structure.

Calculations were made of the cost of neutrally buoyant hulls of a given volume for a range of operating depths, adding buoyancy material as required to achieve neutral buoyancy, particularly at the deeper depths and for the lower strength materials.

Figures 7, 8 and 9 show the results of these calculations for three assumed values of cost per pound of buoyancy. Currently, high-strength buoyancy material is selling for about $8 to $10 per pound of material, in simple shapes such as rectangles or cylinders, although some lower prices frequently appear in journal articles. Depending on the density of the foam, these prices convert to values in the $10 to $20 range per pound of buoyancy. If large quantities were produced, as would be the case for a program of submarines of the ADA type, the price might fall to $5 or less per pound of buoyancy. See Appendix II for further information on cost of buoyancy material.

For the set of assumptions presented, the cost of buoyancy is shown to have an important influence on the total structural cost. For $20/lb buoyancy, in the range of depth of interest to the ADA submarine concept (16,000-18,000 feet), three materials, HY 130, HY 180 and Ti 120 ($20/lb) fall in the range of $8 to $14 per cubic foot of interior volume. At $10/lb of buoyancy, HY 130 is clearly the prime candidate, while at $5/lb of buoyancy HY 80 and HY 130 have equal merit.
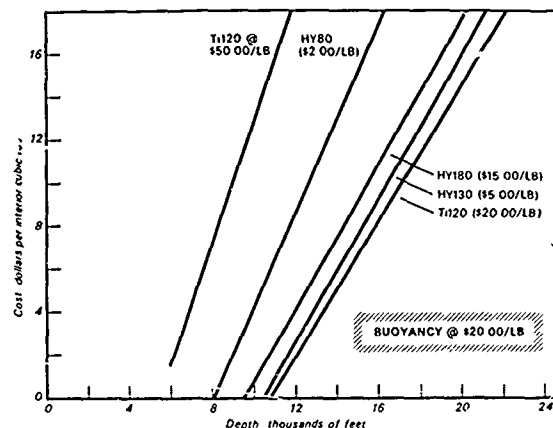

Fig. 7. Pressure hull cost vs. depth for selected materials (buoyancy at $20/lb).

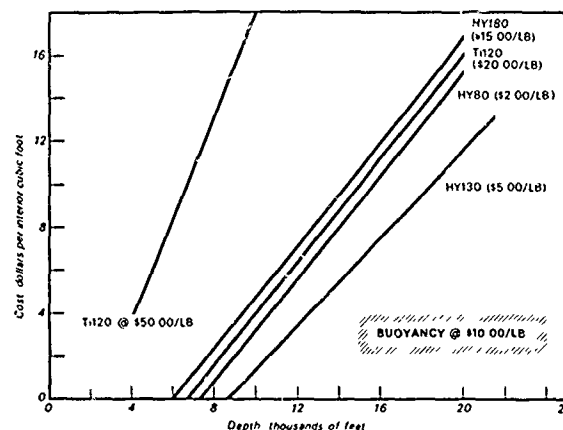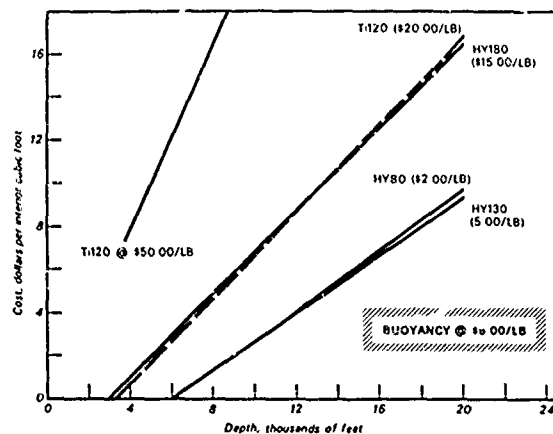Fig. 8. Pressure hull cost vs. depth for selected materials (buoyancy at $10/lb).

Fig. 9. Pressure hull cost vs. depth for selected materials (buoyancy at $5/lb).

IV. ESTIMATE OF VOLUME REQUIREMENT

"D" Hull Volume

A preliminary estimate was made of the volume of pressure-proof hull structure required to contain personnel and those items of equipment incapable of withstanding immersion in the sea and/or deep submergence.

For most items it is convenient to consider the deck area required for each function and to relate the total deck area to that available in an assumed horizontal cylindrical hull unit, with a deck on or near the axis. Tanks for fresh water, fuel and ballast as well as volumes for storerooms and auxiliary machinery may be located in round-bottomed spaces below the deck.

A 15-ft diameter pressure hull cylinder is assumed in this initial estimate. The volume per foot of length is about 175 ft^3 for the full circular section. The below-deck portion would be about 75 ft^3 per foot after deducting an allowance for framing and bulkheads.

Table 1 gives a summary of major volume components of the "D" hull. Use has been made of Appendix C of Ref. 3 which gives several criteria for estimating volume requirements for selected functions of a submarine, based on analysis of drawings of recent submarine classes.

The 3300 ft^2 of above-deck area is equivalent to about 220 feet of length, which is approximately equal to the total length of below-deck volume indicated in the lower part of Table 1.

"A" Hull Volume

The initial conceptual configuration for the "A" hull resembles the current construction of attack submarines, about 30 feet in diameter, but somewhat shorter in length, about 200 feet. as shown in Fig. 10. The total volume, which is estimated to be about 115,000 ft^3, will be compared to the functional volume requirement.

The Ordnance Research Laboratory made a preliminary estimate of 54,000 ft^3 for the volume required for the chemical reactor, fuel, oxidizer, and associated tanks of the propulsion plant, in the "A" hull. This corresponds to a length of about 80 feet of the cylindrical hull. The turbines, gears, and propulsion auxiliaries could probably be fitted into a portion of the conical stern section about 20 feet in length.

Allowing 25 feet of length for propeller and "unusable" (except for ballast tankage) volume at the bow and stern, a length of about 75 feet remains for personnel, weapons, communication and control, sonar, provisions, stores, water, life support and ballast tanks. Using a three-level arrangement, as shown in Fig. 10, a total of approximately 70 ft^2 of deck area, on all three levels, would be available for each foot of length (total of 5250 ft^2). In the lower level, the volume per foot of length is approximately 180 ft^3, for a total of 13,500 ft^3.

Table 2 is a breakdown of the volume of the "A" hull into its principal components. The total volume required exceeds that available in the 75 feet of hull remaining after the propulsion plant and unusable volumes are subtracted. A lengthening of the "A" hull by about 10 feet would readily provide the needed volume, but, in view of the desire to

Table 1. Volume Components of "D" Hull.

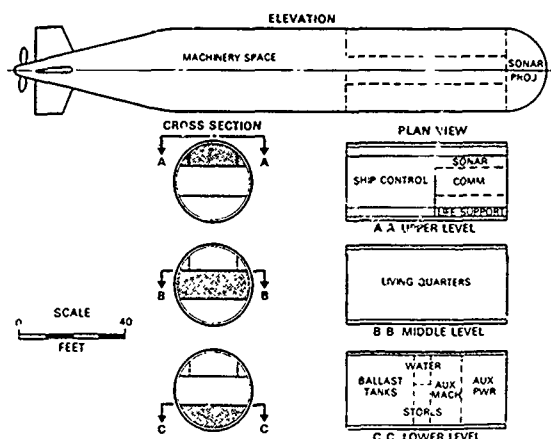| Item	Deck area (ft^2)	Volume (ft^3)	Lineal feet of lower level (ft)
Above-deck items			
Berthing, messing, galley, lounge –			
for 6 officers at 55 ft^2 each	330	---	---
for 50 enlisted men at 28 ft^2 each	1400	---	---
Ship control room	900	---	---
Radar room	100	---	---
Sonar plot room	400	---	---
Communications	200	---	---
Subtotal	3300		
Below-deck items			
Sonar equipment	1000	---	66
Fresh water at 40 gals/man	---	300	4
Sanitary tank at 36 gals/man	---	270	4
Provisions and stores for 100 days at 7.2 lb/man/day	---	2016	28
Variable ballast tankage (approx. vol. of above 3 items)	---	3000	40
Life support	---	1125	15
Auxiliary power and propulsion (fuel cells, fuel supply)	---	2250	30
Miscellaneous auxiliary machinery (pumps, compressors, etc)	---	2250	30
Subtotal	1000	11,211	217
TOTAL	4300*	11,211	217

*on two decks

Fig. 10. Preliminary functional volume assignment for "A" hull.

Table 2. Volume Components of "A" Hull.

Item	Deck area (ft^2)	Volume (ft^3)	Lineal feet of lower level (ft)
Upper level			
Sonar consoles	300	---	---
Communications	300	---	---
Life support	250	---	---
Ship control	900	---	---
Middle level			
9 officers at 55 ft^2	495	---	---
56 enlisted men at 28 ft^2	1570	---	---
Lower level			
Sonar equipment	500	300	2
Provisions and stores (100 days at 7.2 lb/man/day	---	2350	13
Sanitary tank at 36 gals/man	---	315	2
Fresh water at 40 gals/man	---	350	2
Auxiliary power	---	3000	17
Auxiliary machinery	---	3000	17
Ballast tanks (5% of total volume)	---	5650[1]	31[1]
TOTAL	4315	14,965	84

[1] A portion of the ballast tank requirement may be met by utilizing "unusable" volumes near the ends of the hull, reducing these figures by about 10% each.

keep the "A" hull as small as possible and considering the uncertainty of the estimate of volume of the propulsion plant, no change in the dimensions of the "A" hull will be made at this time.

V. THIRD HULL CONCEPT

In the course of the initial phase of the study reported here, the Second Workshop on Advanced Submarine Technology and Design Concepts[2] was held, during which progress of this study and others was reported. The members of the Workshop offered suggestions to enhance the effectiveness of several of the concepts presented. In considering the ADA submarine symbiosis the suggestion was advanced that a third unit, or "C" (cryogenic) hull, might prove a useful addition to the system. The primary functions of this unit would be to manufacture and store cryogenic gases for the use of the "A" and "D" hulls. The "C" hull would need only a limited depth capability since most of its operating time would be spent on or near the surface, using the atmosphere as a source of nitrogen and oxygen. Since the "C" unit need not be stationed in the immediate vicinity of the operating area of the "A" and "D" units, its presence would be unlikely to reveal the location of the latter units. Furthermore, the "C" unit may be considered somewhat less subject to attack, since it is farther from enemy bases than are the other two units.

In considering a number of alternative energy sources for the "A" and "D" units, the idea of manufacturing at sea certain high-energy substances was advanced by members of the Workshop. Hydrazine (N_2H_4) and liquid oxygen (LOX) are well-known for their high-energy output when combined. Hydrogen peroxide (H_2O_2) is another powerful oxidizing agent. Since all three of these substances are made up entirely of elements occurring freely in the atmosphere (N and O) or in the sea (H and O) the possibility of synthesizing them at sea is intriguing.

The simplest process is that of extracting oxygen from the atmosphere, by compression, refrigeration and then separation of the nitrogen and oxygen by making use of the difference in boiling points. Both oxygen and nitrogen may be produced by this process, which is based on the original process of Carl von Linde, perfected in 1895. Today portable units powered by gas turbine or by electric motor are available commercially. One unit selling for about $300,000 is capable of producing 3 tons of liquid oxygen (LOX) per day. United States Navy aircraft carriers and submarine tenders use similar equipment for the production of both nitrogen for inerting aviation fuel tanks and adjacent spaces and oxygen for weapon systems and for recharging submarine oxygen bottles.

Hydrogen peroxide (H_2O_2) is manufactured by electrolytic and organic oxidation processes. The former involves electrolytic production of the peroxydisulfate intermediate, followed by steam hydrolysis to H_2O_2, with regeneration of the original sulfuric acid or ammonium bisulfate raw materials. One organic process uses anthraquinone dissolved in organic solvents. The quinone is catalytically hydrogenated to the hydroquinone; subsequent aeration of the latter regenerates the quinone, with simultaneous formation of H_2O_2. The H_2O_2 is water-extracted and concentrated; the quinone is recycled for reconversion to hydroquinone. A second organic process uses liquid isopropyl alcohol, which is oxidized at moderate temperatures and pressures to H_2O_2 and acetone coproducts. After distillation of the acetone and unreacted alcohol, the residual H_2O_2 is concentrated. It appears that any of these processes would be suitable for use at sea, although the amounts of raw materials consumed, which may be greater for some processes than for others, could be a serious logistic problem.

Hydrazine (N_2H_4) can be made by a number of processes, only two of which are of commercial significance. The first method is commonly referred to as the Raschig process after the German chemist Fritz Raschig, who developed it. In this process an excess of concentrated aqueous ammonia solution is reacted with sodium hypochlorite to yield a dilute solution of hydrazine. Since traces of metallic ions in the solution greatly reduce the yield, glue is usually added to the reaction mixture to overcome their effect. The dilute solution is then concentrated by evaporation to give hydrazine hydrate. The second process is similar except that a sodium hydroxide solution of urea is used instead of ammonia.

Since the primary ingredient of the first process is ammonia (NH_3), it is of interest to outline briefly the process of synthesizing it. The Haber process which is the major source of industrial ammonia involves the process

$$N_2 + 3H_2 \rightarrow 2NH_3 + \text{Heat.}$$
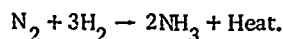
This reaction is carried out under very high pressures, at elevated temperatures, in the presence of a catalyst. Operating conditions vary, but usually the conditions are from 300 to nearly 1000 atmospheres pressure and in the temperature range of 450-600°C. A variety of catalytic materials have been used. The nitrogen would be available from the atmospheric separation outlined above but the source of hydrogen at sea would be more difficult. Commercial ammonia plants ashore obtain the required hydrogen from natural gas. Since liquified natural gas is transported by sea commercially in

bulk quantities of thousands of tons, the technology for storing it aboard ship is available today. If electrolysis of water is seriously considered as the hydrogen source in the making of ammonia, production of H_2 and O_2 to be used in a fuel cell or closed cycle combustion process would appear to be more appropriate than the production of hydrazine.

It is evident from the above descriptions of the processes involved that, except for the production of LOX, some challenging developmental problems must be addressed before the synthesis of high-energy fuel/oxidant systems at sea becomes an attractive alternative. The usefulness of the "C" hull concept must be explored with the above technological limitations in mind.

VI. ANALYSIS OF THE MATING OPERATION

To provide a better understanding of the forces involved as well as the relative motion of the "A" and "D" hulls during the mating or docking operation, a mathematical analysis was made. To simplify the analysis viscous damping forces and "added mass" effects were omitted.

The analysis consists of two parts, (1) the impact of the "A" hull with entrance wall, the latter yielding as it decelerates the "A" hull, and (2) the trajectory of the "A" hull as it bounces off one side of the entrance wall and tends toward the opposite side as it proceeds inward.

Figure 11 illustrates the initial contact and defines the following symbols:

θ = slope of the entrance wall
X = horizontal distance from apex of entrance
Y = vertical distance from apex of entrance
X_1, Y_1 = coordinates of point of initial contact
X', Y' = coordinates of center of gravity (CG) of "A" hull at time of initial contact
ℓ = distance between CG and nose of "A" hull
v = initial approach velocity of "A" hull (shown as a vector)
ψ = angle of inclination of axis of "A" hull
ϕ = angle of inclination of velocity vector of "A" hull

The basic equations involved are:

F_1 = ma_1		(1)
F_2 = ma_2		(2)
$F_2\ell$ = $I\Omega_1$		(3)

where

F_1 and a_1 = components of force and acceleration along axis of the "A" hull
F_2 and a_2 = components of force and acceleration normal to the axis of the "A" hull
m = mass of "A" hull
I = moment of inertia of "A" hull about CG
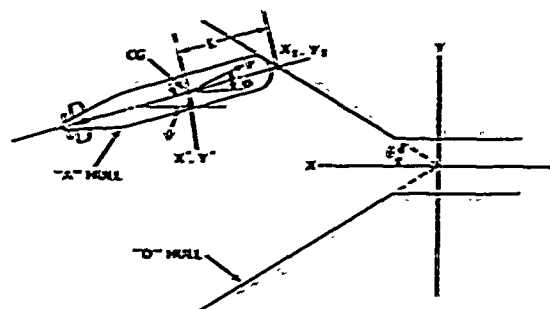Ω_1 = angular acceleration of "A" hull as shown on Fig. 12.

Fig. 11. Docking of "A" hull in "D" hull (position coordinates).
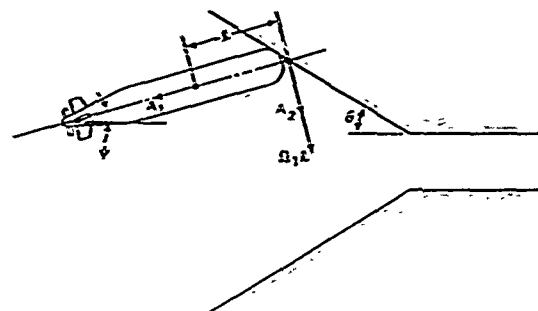

Fig. 12. Docking of "A" hull in "D" hull (acceleration diagram)

Substituting from Eqs. (2) and (3)

$$a_2 = I\Omega_1/m\ell \text{ or the equivalent } a_2 = k^2(\Omega_1/\ell) \quad (4)$$
since $I/m = k^2$ = radius of gyration.
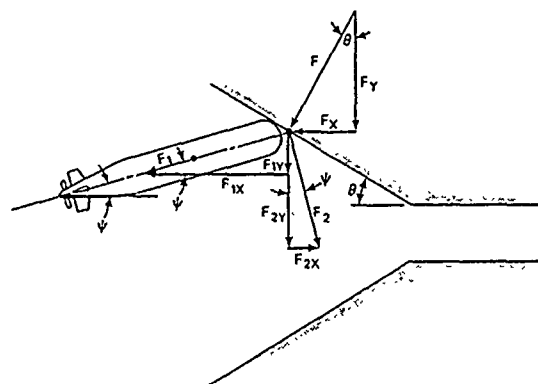
Let F = total force acting on nose of body
F_x, F_y = X and Y components of F
$F_{1x}, F_{2x}, F_{1y}, F_{2y}$ = X and Y components of F_1
and F_2 as shown on Fig. 13.

Fig. 13. Docking of "A" hull in "D" hull (force diagram.

Then
$$F_x = F\sin\theta \quad (5)$$
$$F_y = F\cos\theta \quad (6)$$
$$F_{1x} = F_1\cos\psi \quad (7)$$
$$F_{1y} = F_1\sin\psi \quad (8)$$
$$F_{2x} = F_2\sin\psi \quad (9)$$
$$F_{2y} = F_2\cos\psi \quad (10)$$
$$F_x = F_{1x} - F_{2x} \quad (11)$$
$$F_y = F_{1y} + F_{2y} \quad (12)$$
$$F\sin\theta - F_1\cos\psi + F_2\sin\psi = 0 \quad (13)$$
$$F\cos\theta - F_1\sin\psi - F_2\cos\psi = 0 \quad (14)$$

Substituting from Eqs. (1) and (2)
$$F\sin\theta - ma_1\cos\psi + ma_2\sin\psi = 0 \quad (15)$$
$$F\cos\theta - ma_1\sin\psi - ma_2\cos\psi = 0. \quad (16)$$

Dividing Eq. (15) by $\sin\theta$ and Eq. (16) by $\cos\theta$, subtracting Eq. (16) from Eq. (15) and dividing through by m

$$-a_1\frac{\cos\psi}{\sin\theta} + a_1\frac{\sin\psi}{\cos\theta} + a_2\frac{\sin\psi}{\sin\theta} + a_2\frac{\cos\psi}{\cos\theta} = 0 \quad (17)$$

or
$$a_1\left(\frac{\sin\psi}{\cos\theta} - \frac{\cos\psi}{\sin\theta}\right) + a_2\left(\frac{\sin\psi}{\sin\theta} + \frac{\cos\psi}{\cos\theta}\right) = 0. \quad (18)$$

Let $\left(\frac{\sin\psi}{\cos\theta} - \frac{\cos\psi}{\sin\theta}\right) = A$ and $\left(\frac{\sin\psi}{\sin\theta} + \frac{\cos\psi}{\cos\theta}\right) = B$,

then $A \cdot a_1 + B \cdot a_2 = 0.$ (19)

If a_{max} = maximum permissible acceleration
$$(a_{max})^2 = a_1^2 + (a_2 + \Omega_i\ell)^2. \quad (20)$$
Substituting from Eq. (4)
$$(a_{max})^2 = a_1^2 + [k^2(\Omega_1/\ell) + \Omega_1\ell]^2. \quad (21)$$
Let $\ell_1 = (k^2/\ell) + \ell$ and solve for a_1
$$a_1 = \sqrt{(a_{max})^2 - (\Omega_1\ell_1)^2} \quad (22)$$
$$A\sqrt{(a_{max})^2 - (\Omega_1\ell_1)^2} + B(k^2\Omega_1/\ell) = 0 \quad (23)$$
$$A^2[(a_{max})^2 - (\Omega_1\ell_1)^2] = B^2(k^4\Omega_1^2/\ell^2) \quad (24)$$
$$\Omega_1 = \frac{a_{max}}{\sqrt{(\ell_1)^2 + (B/A \cdot k^2/\ell)^2}} \quad (25)$$

Assuming that the "A" hull will be decelerated to zero velocity by the action of the shock mitigation system in the entrance way, and assuming a uniform deceleration, the duration of the contact (t_c) with the entrance way may be expressed as

$$t_c = v_n/a_n \quad (26)$$

where v_n = component of initial velocity normal to the entrance way,

a_n = component of deceleration normal to the entrance way.

This may be evaluated by taking components of the velocity and acceleration to give the equation

$$t_c = \frac{v\cos\phi \div \omega \ell \sin\psi}{a_1\cos\psi \div (a_2 \div \Omega_1 \ell)\sin\psi} \qquad (27)$$

where

ϕ = angle of initial velocity of center of gravity,
ω = initial angular velocity of the "A" hull.

The maximum deflection (d_{max}) of the entrance way shock mitigation system during the impact may be found from the equation

$$d_{max} = \frac{1}{2} a_n \cdot (t_c)^2. \qquad (28)$$

For this condition, the values of v, ω, ψ, X_1, Y_1, X', and Y' which are slightly changed from the values at initial contact, may be calculated.

As a result of the impact, the "A" hull will be deflected toward the other side of the entrance way. Assuming uniform motion the trajectory of the nose of the "A" hull as it travels across the entrance and the coordinates of the second point of impact may be calculated.

$$X = X_1' + v_{1x}t \div \ell\cos(\psi_1 - \omega_1 t) \qquad (29)$$

$$Y = Y_1' + v_{1y}t \div \ell\sin(\psi_1 - \omega_1 t) \qquad (30)$$

$$Y = X\tan\theta \text{ at second impact} \qquad (31)$$

where

X_1', v_1, ψ_1, ω_1 refer to values at the position of maximum deflection
t = time after maximum deflection is reached.

A computer program was prepared to solve for t, X, and Y and to calculate new values of velocity, acceleration, and angle of the "A" hull.

A series of calculations were made for a range of values of θ, ψ, ϕ, and Y. The results are shown in Figs. 14 through 25.

Figures 14 through 17 show the variation in the X dimension of the point of second impact with the above parameters.

Figures 18 through 21 show the variation in the maximum deflection at the initial impact (D_1) and at the second impact (D_2). In a few cases a third impact was indicated and values for maximum deflection are shown by curve D_3.

Figures 22 through 25 show the variation in the angle of the "A" unit at second impact (ψ_2) with the same parameters. A few cases of third impact are also shown (ψ_3).

These curves were useful in determining reasonable values of entrance angle and maximum deflection for the experimental models which are being designed.
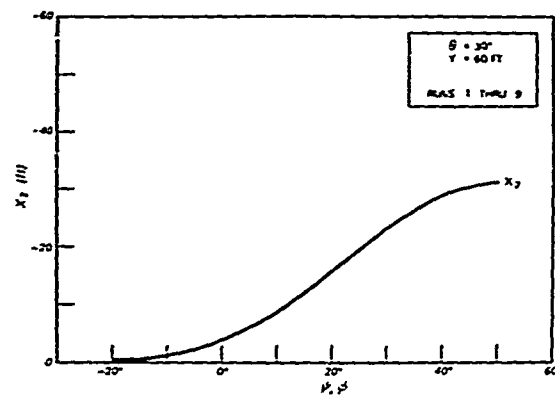
Fig. 14. Solution of docking impact equations — distance vs. angle of "A" hull and angle of velocity of "A" hull.
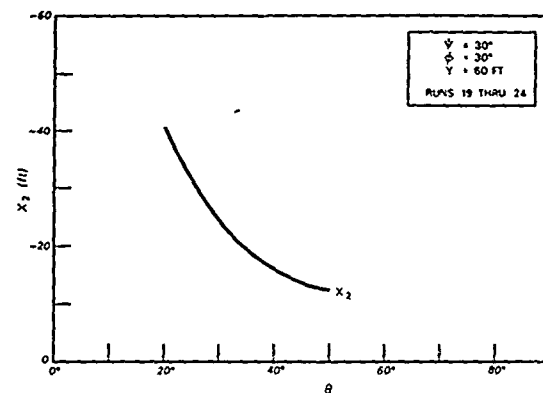
Fig. 15. Solution of docking impact equations — distance vs. entrance angle.
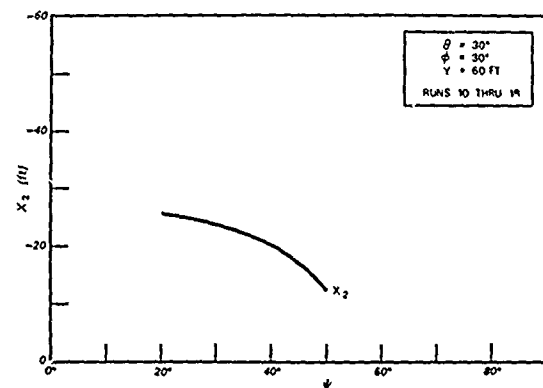
Fig. 16. Solution of docking impact equations — distance vs. angle of "A" hull.

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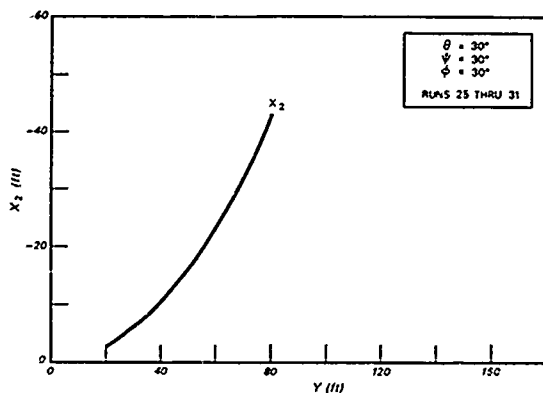
Fig. 17. Solution of docking impact equations — distance vs. location of initial impact point.
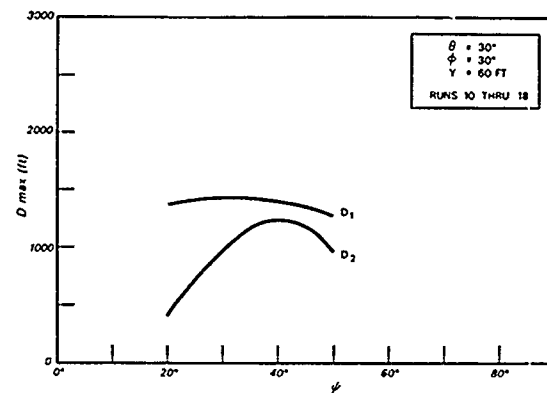

Fig. 20. Solution of docking impact equations — deflection of shock mitigator vs. entrance angle.
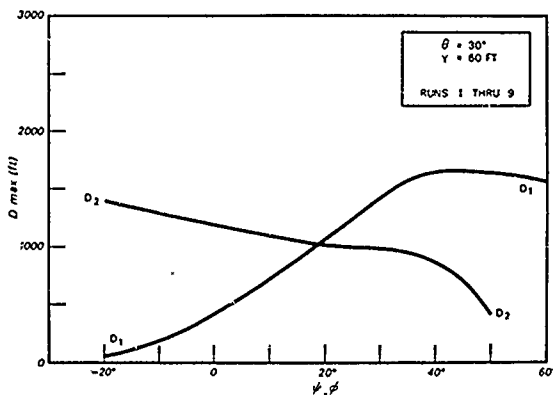

Fig. 18. Solution of docking impact equations — deflection of shock mitigator vs angle of "A" hull and angle of velocity of "A" hull.
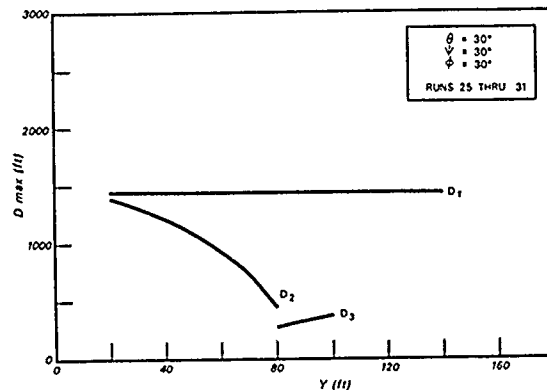

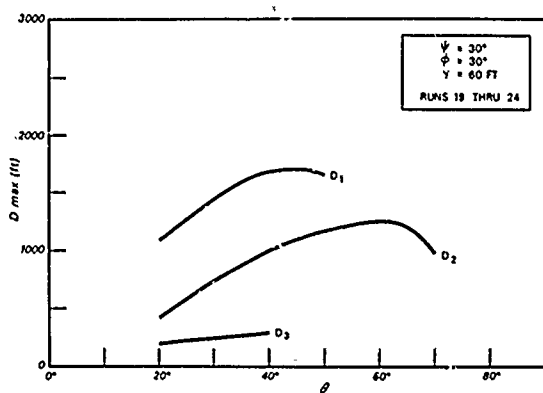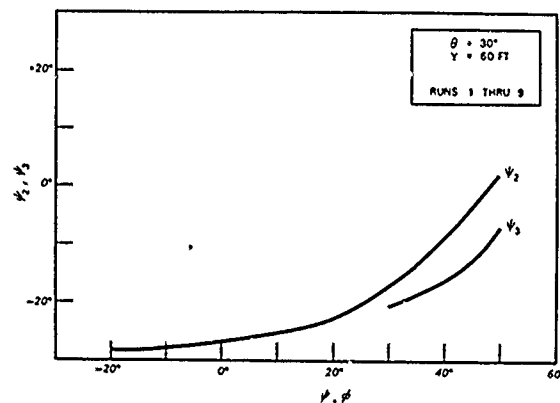Fig. 21. Solution of docking impact equations — deflection of shock mitigator vs. location of initial impact point.

Fig. 19. Solution of docking impact equations — deflection of shock mitigator vs. angle of "A" hull.

Fig. 22. Solution of docking impact equations — angle of "A" hull after impact vs. angle of hull and angle of velocity before impact.
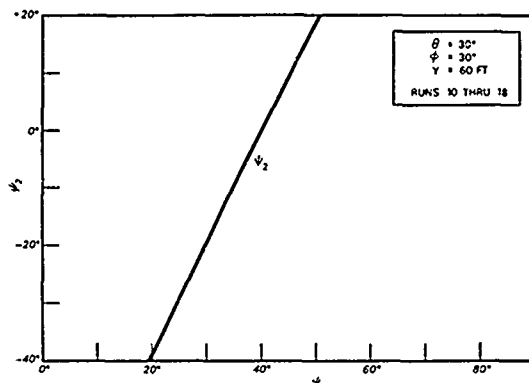
Fig. 23. Solution of docking impact equations — angle of "A" hull after impact vs. angle of hull before impact.
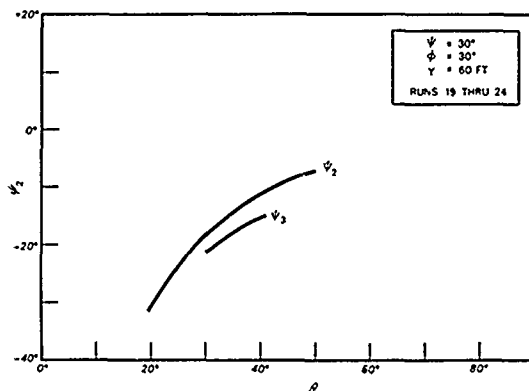
Fig. 24. Solution of docking impact equations — angle of "A" hull after impact vs. entrance angle.
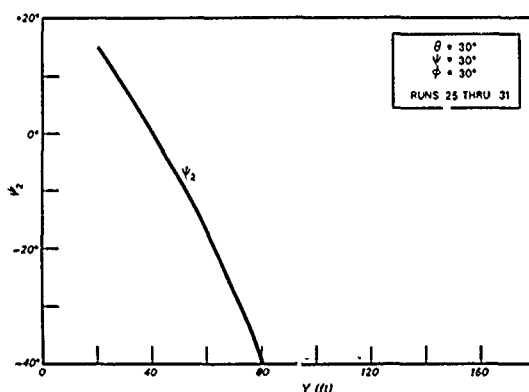
Fig. 25. Solution of docking impact equations — angle of "A" hull after impact vs. location of initial impact point.

VII. CONCLUDING REMARKS

As a result of these initial studies, two main areas of technology have emerged as candidates for further investigation.

One of these is the large aperture passive sonar. The configuration of Fig. 4 is conceptual in nature. There are many problem areas in deep submergence absorber materials, array element isolation, dome configuration and signal processing which can profitably be explored on an experimental basis.

Further exploration of the mating system would also be appropriate. This could be done experimentally, accompanied by supporting theoretical work as required. Trade-offs between the extent of manual and automatic control and the type of status display during the docking operation needs to be investigated. The mechanical latching of the two hulls is an area of needed development. Model tests, first on a small scale in a towing tank and later with a small manned submersible, would be of great benefit in obtaining answers in these problem areas.

APPENDIX I

OPTIMUM FREQUENCY FOR AN ADA DETECTION SONAR

In proceeding with a conceptual design for the passive sonar of an ADA submarine, some first-cut estimate of a suitable operating frequency band must be made. Unfortunately, data on noise directivity and fluctuation statistics are sparse at best, and estimates must be made using data which are not directly applicable to sound channel listening depths, i.e., 1-4000 feet.

In order to establish the constraints of the problem to permit an optimization, the following assumptions will be made:

1. A fixed billboard aperture 30 feet high (vertical) x 120 feet long (horizontal).

2. Deep water background vertical directivity as given by Axelrod et al.[4]

3. Inverse square spreading.

4. Continuous array for beam pattern calculations.

5. A target spectrum as given by Urick.[5]

6. 100-second averaging time for detection.

7. Optimization will be carried out for the broadside beam pattern.

The approach to the selection of an optimum frequency takes the following path:

Consider a background field which is azimuthally isotropic and has a vertical directionality as given by Axelrod et al.[4] It is noted that the measurements are of deep water noise and not necessarily directly applicable to a 1-4000 ft listening depth, but they represent the best set of measurements presently available for a noise model.

Assuming that the array gain will be high—and that correspondingly, the beamwidth will be small, a linear approximation to the beam pattern gives a separable expression:

$$\text{Horizontal } b(\theta) = \frac{\sin(\pi L/\lambda \sin\theta)}{(\pi L/\lambda)\sin\theta}$$

where L = array length, λ = wavelength, θ = azimuthal angle from array normal; for small angles,

$$\text{l/? power width } \theta_0 \simeq L(\text{length})/\lambda.$$

$$\text{Vertical } b(\psi) = \frac{\sin(\pi H/\lambda \cos\psi)}{(\pi H/\lambda (\sin\psi/\cos\psi))}$$

where ψ is the polar angle (array normal is at $\psi = \pi/2$), H = array height. The noise spectrum level output of the array then will be given approximately by

$$N \simeq (2\pi/\theta_0) \int_0^\pi N(\psi) \frac{\sin(\pi H/\lambda \cos\psi)}{\pi H/\lambda \cos\psi} 2\pi \sin\psi \, d\psi \cdot$$

where $N(\psi)$ is the angular noise power spectrum level. The approximation arises from the use of a fixed azimuthal beamwidth θ_0 which is in error for polar angles approaching the axis.

A vertical directivity model derived from data of Axelrod et al. for Beaufort 6 given in Table I-1 will be used. No data are given for angles lower than horizontal and thus to be conservative the model is mirrored around 90°. Numerical integration of the data of Table I-1 generated the array noise spectrum level curves of Fig. I-1.

Table I-1

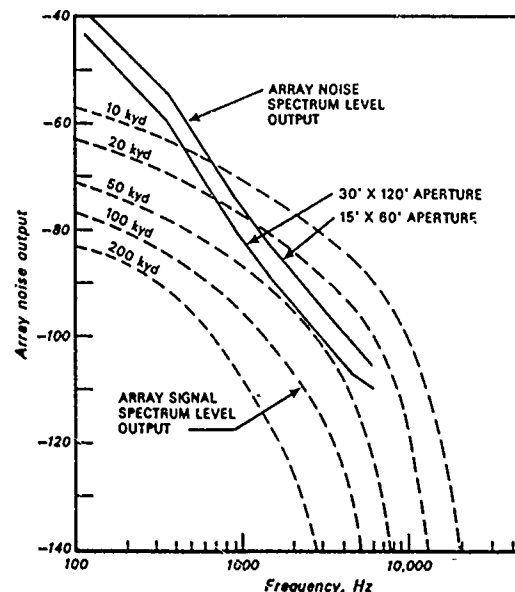| ψ	FREQUENCY			
	112	355	891	1414
0	-49	-42	-46	-50
10	-48	-42	-46	-50
20	-46.5	-42	-46	-50
30	-45.5	-42	-46	-50
40	-44	-43	-47	-51
50	-42.5	-44	-48	-54
60	-40.5	-45	-50	-56
70	-38	-45	-52	-57.5
80	-35	-43	-54	-59
90	-32	-41	-55	-59

Fig. I-1. Array noise and signal spectrum level outputs vs. frequency.

For a target characteristic we use data from Urick[5] (Fig. 10.16) for four-knot periscope depth target smoothed spectrum

$$S_L = 33 \text{ dB at } 100 \text{ Hz}$$
$$20 \text{ dB at } 1000 \text{ Hz}$$
$$0 \text{ dB at } 10,000 \text{ Hz}.$$

These data are for periscope depth WWII submarines and should be more or less representative of a typical present-day deep target. For the purpose of conservative optimization an over-all drop of 10 dB will be assumed. The optimization is not particularly sensitive to detailed target characteristics, thus this approximate "ball park" spectrum should give a valid guide to array optimization. Values read from a smoothed curve fitted to the above three points are given in Table I-2. These will be used as a target model.

Table I-2. Target Model

Frequency	Source Level dB re 1 μbar at 1 yd
100	23.0
200	20.0
500	14.7
1000	10.0
2000	5.0
5000	-2.5
10000	-10.0
20000	-18.0

As a propagation model, $1/R^2$ will be used with attenuation loss given by $\alpha = 0.1 \, f^2/(1 + f^2) + 40 \, f^2/(4100 + f^2)$ (dB/kyd), f in kHz as given by Thorpe.[5] The use of inverse square spreading as a valid model is substantiated by a wide variety of experimental measurements as pointed out by Urick[5] (pg. 92).

Combining the array characteristics and the noise model for two aperture sizes, 15' x 60' and 30' x 120' the array noise spectrum level output curves of Fig. I-1 are obtained (solid lines). The combination of the propagation and target models gives rise to the signal spectrum level curves of the same figure (dashed lines). The differences between the 30' x 120' curve and the signal spectrum level curves yield the S/N spectrum level curves of Fig. I-2.
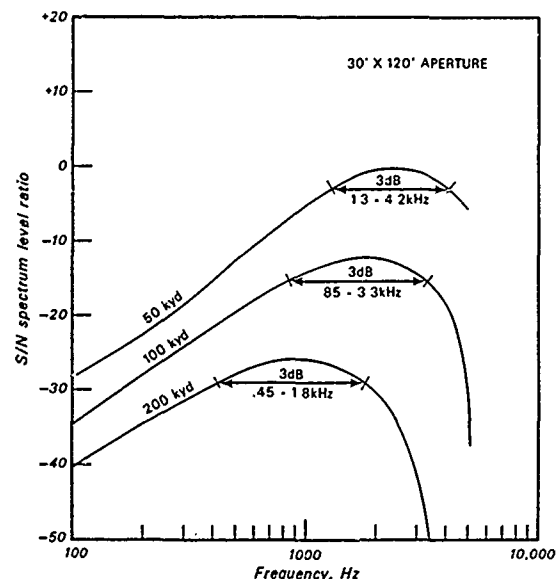
Fig. I-2. Signal to noise spectrum level ratio vs. frequency.

As can be seen from Fig. I-2, the 3 dB S/N bandwidths are of the order of 2 octaves, virtually independent of range. The significant shift of operating frequency occurs with the increment from 100 kyd to 200 kyd where a shift of 2.1 in center frequency occurs. An initial selection of operating frequency band is based on the 100 kyd curve. This selection does not differ greatly from that for the 50 kyd range. This S/N ratio combined with a 22 dB post-detection processing gain [5 log (2.5 x 10^3 (Hz) x 10^2 (sec))] provides an adequate signal excess to meet a 10 dB recognition differential threshold. The upper operating frequency of the array would thus be slightly less than 4 kHz.

For a one-half λ spacing of array elements at the mean effective band center frequency (2.2 kHz) a full-sized 30' x 120' aperture would contain 3080 elements on a 1.1-ft spacing. A one-half sized aperture operating at the same center frequency would contain 840 elements.

APPENDIX II

One producer (Emerson and Cuming, Inc.,
Canton, MA) of buoyancy materials presented the
information shown in Table II-1.

Table II-1. Characteristics and Cost of Several Buoyancy Materials

| Materials | Characteristics | | | Cost | | |
	Density (lb/ft^3)	Compressive Strength (lb/in^2)	Unit	1-9 (ea)	Quantities 10-99 (ea)	>99 (ea)
PG 23	23	2000	kit, 1 ft^3	$125.00	$105.00	$87.00
PG 35			kit, 1/4 ft^3	25.00	22.50	---
PG 35	35	2200	kit, 1 ft^3	81.00	66.00	---
PG 35			kit, 3 ft^3	225.00	180.00	---
STYCAST 1421			kit, 1 lb	12.00	---	---
STYCAST 1421	42	11,000	kit, 11 lb	6.95/lb	---	---
STYCAST 1421			kit, 54 lb	6.75/lb	---	---
PC 69*	43	12,000	kit, 90 lb	2.50 to 3.50/lb (est)	---	---

* A new product not yet on market — cost is approximate.

These costs, some in terms of volume and
some in terms of weight, may be put on a compara-
ble basis of cost per pound of buoyancy. The results
are shown in Table II-2.

Table II-2. Cost per Pound of Buoyancy of Materials
Listed in Table II-1

Material	Cost per pound of buoyancy
PG 23	$2.12
PG 35	2.07
STYCAST 1421	12.90
PC 69	5.11 to 7.15

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2. Spiess, F. N., ARPA Workshop on Advanced
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Card 1 (top-left)

Marine Physical Laboratory
MPL-C-70/71

ADA SEPARABLE SUBMARINE STUDY (U) by Victor C. Anderson and H.P. Rumble, University of California, San Diego, Marine Physical Laboratory of the Scripps Institution of Oceanography, San Diego, California 92152. *SIO Reference 71-26, 15 October 1971.*

This is a summary of the initial study phase for the ADA(Advanced Detection Attack) separable submarine. The contrasting functions of the two units are described and a number of alternative configurations are presented. Trade-offs between cost of structural materials and cost of buoyancy materials are shown graphically, with an indication of the least cost combination. Preliminary volume estimates are given for each of the hulls. A suggested alternative scheme involving three hulls instead of two is discussed. Selected aspects of the mating or docking operation are analyzed mathematically, and parametric curves showing the relationships among the important factors are presented. A preliminary estimate of the optimum frequency for a passive detection sonar array is calculated.

Card 2 (bottom-left)

Card 3 (top-right)